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14. ABSTRACT

[1] Theoretical study of electron density distribution in the nighttime equatorial ionosphere shows that linear relationships with statistically significant correlation coefficients exist between the maximum value of the post-sunset plasma drift velocity and the peak-to-valley ratio of anomaly TEC. The study is based on the low-latitude density model of Air Force Research Laboratory (AFRL) and the obtained relationships are valid for the longitudinal sector of Jicamarca incoherent scatter radar whose drift velocity measurements are used. The significance of this finding lies in the fact that the maximum value of the post-sunset vertical plasma drift velocity is an important parameter for determining both the intensity and the latitudinal distribution of equatorial scintillation. When the parameter is not available from any direct measurement, the linear relationships may be used to estimate it from the measured peak-to-valley ratio of anomaly TEC.

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Theoretical relationship between maximum value of the post-sunset drift velocity and peak-to-valley ratio of anomaly TEC

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[1] Theoretical study of electron density distribution in the nighttime equatorial ionosphere shows that linear relationships with statistically significant correlation coefficients exist between the maximum value of the post-sunset plasma drift velocity and the peak-to-valley ratio of anomaly TEC. The study is based on the low-latitude density model of Air Force Research Laboratory (AFRL) and the obtained relationships are valid for the longitudinal sector of Jicamarca incoherent scatter radar whose drift velocity measurements are used. The significance of this finding lies in the fact that the maximum value of the post-sunset vertical plasma drift velocity is an important parameter for determining both the intensity and the latitudinal distribution of equatorial scintillation. When the parameter is not available from any direct measurement, the linear relationships may be used to estimate it from the measured peak-to-valley ratio of anomaly TEC. *INDEX TERMS:* 2411 Ionosphere: Electric fields (2712); 2415 Ionosphere: Equatorial ionosphere; 2437 Ionosphere: Ionospheric dynamics; 2447 Ionosphere: Modeling and forecasting; *KEYWORDS:* nighttime equatorial anomaly, TEC, post-sunset drift velocity, scintillation. **Citation:** Basu, B., J. M. Retterer, O. de La Beaujardière, C. E. Valladares, and E. Kudeki (2004), Theoretical relationship between maximum value of the post-sunset drift velocity and peak-to-valley ratio of anomaly TEC, *Geophys. Res. Lett.*, *31*, L03807, doi:10.1029/2003GL018725.

1. Introduction

[2] Scintillation caused by density fluctuations (irregularities) in the ionosphere results in outages of the communication and navigation systems that depend on trans-ionospheric radio links. The outages can be particularly severe at equatorial latitudes in the post-sunset hours, when scintillation is caused by the occurrence of so-called plasma 'bubbles' (structures with depleted density) that are formed as the result of collisional interchange plasma instability known as the generalized Rayleigh-Taylor (R-T) instability. The instability is excited on the bottomside of the F layer, where a sharp upward density gradient develops after sunset due to rapid recombination of electrons and ions, and it is driven by the combined effects of the gravity, the eastward electric field and the vertically downward neutral wind velocity. Subsequent nonlinear development of the instability leads to the formation of the 'bubbles'.

[3] The eastward electric field, which is enhanced over its daytime value after sunset and which attains a maximum value before reversing its direction, induces vertically upward $\mathbf{E} \times \mathbf{B}$ plasma drift. This pre-reversal enhanced upward drift velocity plays important roles in the dynamics of the post-sunset equatorial ionosphere. First, it is responsible for the pronounced Appleton anomaly, which is formed when the vertically uplifted plasma diffuses along the Earth's magnetic field due to gravity and pressure gradient forces. The structure of the anomaly, including the magnitudes of the anomaly crests and their locations, critically depends on the maximum value of the vertical plasma drift velocity [*Bramley and Peart*, 1965; *Anderson*, 1973]. Second, the drift velocity plays a major role in the linear growth of the generalized R-T instability [see e.g., *Kelley*, 1989; *Basu*, 2002]. As for its effect on the nonlinear evolution of the instability, strong correlation between the maximum value of the post-sunset vertical velocity and the occurrence of 'bubbles' through nonlinear processes has been demonstrated both theoretically [*Retterer et al.*, Assimilative modeling of the equatorial ionosphere for scintillation forecasting: Modeling with vertical drifts. Submitted to JGR] and observationally [*Fejer et al.*, 1999; *Whalen*, 2001]. Furthermore, *Whalen* [2000] has shown that scintillation is most disruptive when a 'bubble' intersects the maximum electron density of the Appleton anomaly, the magnitude of which, as mentioned above, critically depends on the maximum value of the post-sunset drift velocity. In short, the maximum value of the post-sunset vertical drift velocity is an important, perhaps the most important, parameter for determining both the intensity and the latitudinal distribution of equatorial scintillation.

[4] In this Letter, we present results from theoretical calculations, which suggest that linear relationships exist between the maximum value of the post-sunset vertical drift velocity and the peak-to-valley ratio of anomaly total electron content (TEC). When the drift velocity information is not available from any direct measurement, the relationships may be used to estimate the maximum value of the drift velocity from the peak-to-valley ratio of the anomaly TEC, which, for instance, can be derived from the ultraviolet (UV) imagery data of TEC in the anomaly region. Such UV data are acquired by GUVI on TIMED and will hopefully be acquired by SSUSI on DMSP and by similar instrument on NPOESS satellite. The theoretical calculations are based on the low-latitude ambient plasma density model that has been developed at the Air

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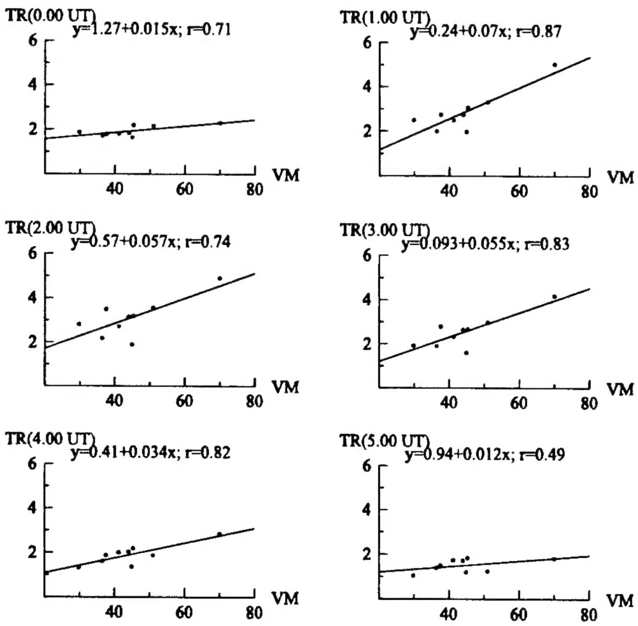

Figure 1. Scatter plots of the peak-to-valley ratio (TR) of calculated TEC in the northern anomaly vs. maximum drift velocity (VM) for six selected times (UT). The slope and intercept of the regression line as well as the correlation coefficient (r) are indicated in each panel.

Force Research Laboratory (AFRL) in support of the satellite-based Communication/Navigation Outage Forecasting System (C/NOFS) mission [*de La Beaujardière et al.*, 2003a, 2003b].

2. Low-Latitude Ambient Plasma Density Model

[5] The AFRL low-latitude plasma model [*Retterer et al.*, Assimilative modeling of the equatorial ionosphere for scintillation forecasting: Modeling with vertical drifts. Submitted to JGR] solves the O^+ continuity equation as a function of time and of position along a field line for a series of flux tubes over a range of field-line apex altitudes. It is thus able to calculate the O^+ density as a function of altitude and latitude at a specified longitude and time. The model is based on the LOWLAT model of *Anderson* [1973]. Instead of the tilted dipole coordinate system commonly used in versions of LOWLAT, the new AFRL model uses field line traced from the IGRF model [*Langel*, 1992] of the geomagnetic field.

[6] In order to solve the continuity equation, several input parameters must be specified as functions of location, time, solar activity and geomagnetic activity. These input parameters are: (a) densities of neutral atmospheric constituents, N_2, O_2, and O, and their temperatures; (b) horizontal and vertical components of the neutral wind velocity; (c) electron and ion temperatures; and (d) zonal and vertical ion drifts. In the present study, the vertical ion drift velocities measured by the Jicamarca incoherent scatter radar (11.95°S, 76.87°W geographic) are used. The other input parameters are specified by standard empirical models [*Retterer et al.*, Assimilative modeling of the equatorial ionosphere for scintillation forecasting: Modeling with vertical drifts. Submitted to JGR]. Specifically, the F region average values of the drift measurements for fourteen days in 2002 (April 15–17, May 31–June 1, June 3–4, October 8–10, and November 11–14), representing both equinox and solstice conditions, are used. The peak value of the post-sunset drift velocity on these days ranges from about 10 m/s to about 70 m/s and so the data set is suitable for the present study. Solar conditions are moderate for these days with the daily $F_{10.7}$ cm flux ranging from 170–200 units and the 3 hr average value of Kp ranges from 1.5–6.0.

[7] Integration of ion density (electron density is taken to be equal to ion density) along altitudes (from 90 km to 1600 km) yields the latitudinal profiles of TEC at the Jicamarca longitude at different times. From the latitudinal distribution of the calculated TEC, the various anomaly parameters such as the location and magnitude of the anomaly crests, the width of the anomaly crests, and the peak-to-valley ratio of anomaly TEC (between the crests and the equatorial TEC minimum), etc. are determined. Repeating the calculations for different days, the coefficients of correlation between the anomaly parameters and the peak value of the drift velocity are calculated, and the scaling relationships between them are then determined by means of least squares fit.

3. Results

[8] We find that significant correlation exists only between the peak value of the post-sunset drift velocity and the peak-to-valley ratio of anomaly TEC. Figures 1 and 2show the scatter plots of the peak-to-valley ratio (TR) of model calculated TEC vs. maximum drift velocity (VM) for the northern and the southern anomalies, respectively. The six panels in each figure are for six selected times indicated therein. We have excluded from Figures 1 and 2 the days when the peak value of the drift velocity is smaller than 30 m/s. The reason for it is that the empirical studies [*Fejer et al.*, 1999; *Whalen*, 2001] indicate a threshold value of the peak vertical velocity (~40 m/s) for scintillations to occur. The straight line in each panel is the least squares fit to the

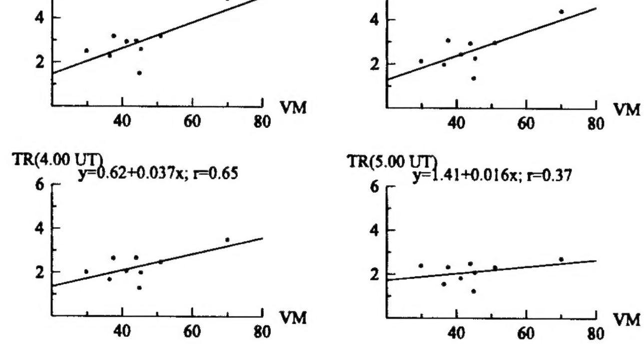

Figure 2. As in Figure 1, but for peak-to-valley ratio of calculated TEC in the southern anomaly.

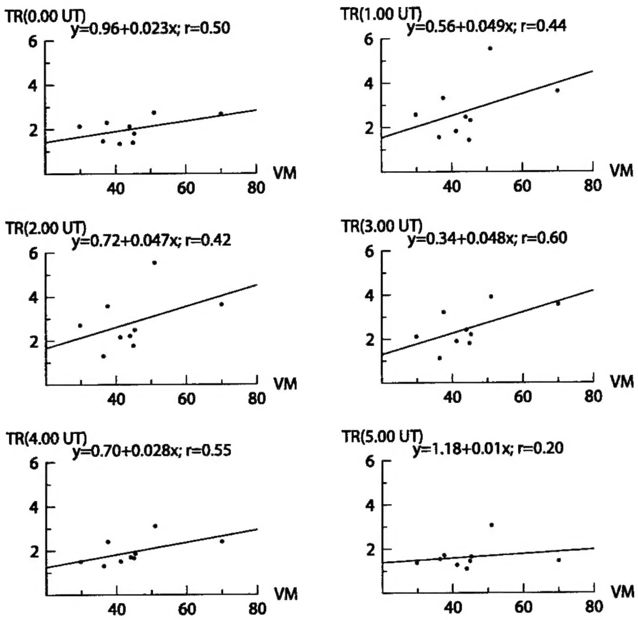

Figure 3. As in Figure 1, but for peak-to-valley ratio of GPS measured TEC in the northern anomaly.

scatter plot. The slope and intercept of the straight line (in the form of y = a + bx) as well as the value of the linear correlation coefficient (r) are indicated in each panel. In both cases, the peak-to-valley ratios are almost independent of the drift velocity at 0000 UT (~1900 LT), which is about the time when the vertical plasma velocity on each day reaches its maximum value. But, a definite linear dependence with significant correlation coefficient starts to develop beginning at 0100 UT (~2000 LT). This is physically explainable since it takes at least an hour for the ionosphere to 'feel' the effect of the post-sunset enhanced drift velocity. The linear dependence persists for at least three hours. However, both the slope and the intercept of the regression lines change with time. Considering the correlation coefficients such as those at 0100–0400 UT in Figures 1 and 2, and referring to Table C-3 given in *Bevington* [1969] we find that the probability of determining such correlation from an uncorrelated population is less than 0.02 and 0.05, respectively. This means that the probability is high that TR and VM are linearly correlated. The estimated standard deviation σ [*Bevington*, 1969] is: $\sigma \cong 0.17$, 0.49, 0.64, 0.46, 0.28 and 0.27, respectively for the six panels in Figure 1. The corresponding uncertainties in the coefficients a and b, denoted by σ_a and σ_b, are: $\sigma_a \cong 0.25$, 0.7, 0.91, 0.65, 0.4, 0.38, and $\sigma_b \cong 0.005$, 0.015, 0.02, 0.014, 0.009, 0.008, respectively. Same values for the six panels in Figure 2 are: $\sigma \cong 0.24$, 0.55, 0.67, 0.64, 0.52, 0.48; $\sigma_a \cong$ 0.34, 0.78, 0.96, 0.91, 0.74, 0.68; and $\sigma_b \cong 0.007$, 0.017, 0.021, 0.02, 0.016, 0.015, respectively. It can be seen from the figures that most contributions to the σ's come from the two points corresponding to VM $\cong$ 37.5 and 45.0, which have large deviations from the fitted straight lines. Jicamarca data show that the temporal profiles of drift velocity on these two days are quite different (large fluctuations both before sunset and after post-sunset reversal) from the other days. This may explain the large deviations of the two points from the fitted straight lines, which result in the large values of the σ's.

[9] For comparison, we determined the peak-to-valley ratios of anomaly TEC for the same days by using the data from a low-latitude chain of 10 GPS receivers that are located near the west coast of South America (~73°W geographic longitude), which is close to the longitude of Jicamarca radar, extending between 5°N and 37°S (geographic latitudes). For detailed discussion of data acquisition and processing, see *Valladares et al.* [2001]. Briefly, the absolute value of TEC is calculated by combining the pseudorange and the GPS signal phase and by adding the receiver and satellite biases. The line-of-sight (oblique) TEC values are merged with ephemeris values of the sub-ionospheric locations to compute the equivalent vertical TEC. Error due to the latitudinal variability of the plasmasphere contribution is minimized by restricting the data used in processing to satellite elevations larger than 35°.

[10] Figures 3 and 4 show the scatter plots of the peak-to-valley ratio (TR) of GPS measured TEC vs. maximum drift velocity (VM) for the northern and the southern anomalies, respectively. The six panels in each figure are for six selected times indicated therein. The straight line in each panel is the least squares fit to the scatter plot, and the slope and intercept of the straight line as well as the value of the correlation coefficient (r) are indicated in each panel. The correlation coefficients are evidently smaller than those obtained for the model results (see Figures 1 and 2) at all times. Interestingly, if the somewhat stray data point corresponding to VM $\cong$ 51 m/s is excluded from Figure 4, the correlation coefficients at 0100 UT and 0200 UT become 0.78 and 0.72, which are comparable to those for the model results.

[11] For validation, we used the linear relations at 0300 UT to estimate VM from the peak-to-valley ratios of TEC measured by GPS receivers on three days in 2001 (September 17, 18 and December 11). The peak-to-valley ratios

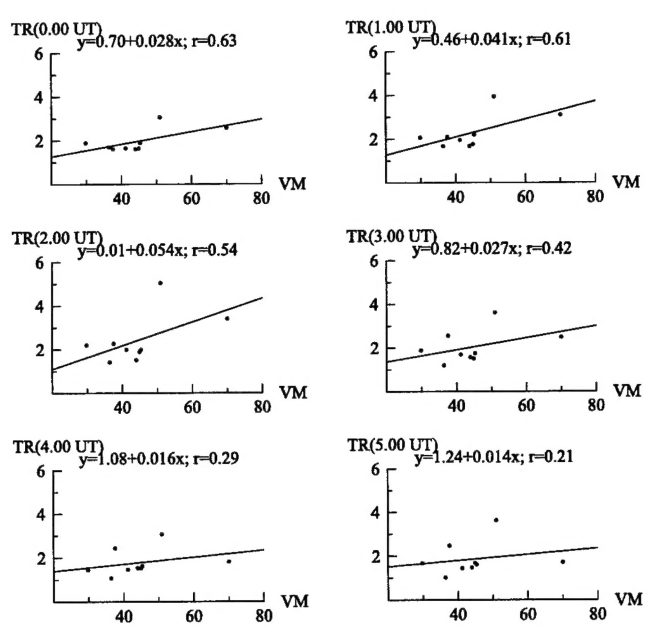

Figure 4. As in Figure 1, but for peak-to-valley ratio of GPS measured TEC in the southern anomaly.

(TR) at 0300 UT are found to be 2.3, 2.81 and 3.45 in the northern anomaly and 2.1, 2.41 and 2.0 in the southern anomaly. The value of TEC at the northern anomaly crest on December 11 was unusually large compared to that at the southern anomaly crest, perhaps due to unusual meridional neutral wind. The estimated values of VM are 40.1, 49.4, and 59.6 m/s, if we use the relation for the northern anomaly; and are 35.1, 40.7 and 33.3 m/s, if we use the relation for the southern anomaly. The Jicamarca measured values of VM are 53.8, 52.5, and 41 m/s, respectively, on these days.

4. Conclusions

[12] Theoretical study of the nighttime equatorial anomaly suggests that linear relationships with high probability exist between the maximum value of the post-sunset enhanced plasma drift velocity (VM) and the peak-to-valley ratio (TR) of anomaly TEC. The relationships are obtained for the longitudinal sector of the Jicamarca incoherent scatter radar whose drift velocity measurements have been used in the theoretical model. The calculations of TEC have been done with a rather limited set of drift data, using climatological models for the other important input parameters. A crucially important parameter in this respect is the meridional neutral wind velocity. In order to have more confidence in the coefficients a and b and thus to have more accurate predictive capability of the theoretical relationships, calculations need to be done with more drift data, using either real-time data or data-driven improved models for the other input parameters. Nevertheless, the linear correlation between TR and VM suggested by the present work cannot be ruled out. The linear relationships may be used to estimate the maximum value of the post-sunset drift velocity from the measured value of the peak-to-valley ratios of anomaly TEC, when the Jicamarca drift data are not available. The temporal variation of the coefficients a and b in the relations must of course be taken into account in any such application. The estimated drift velocity may then be assimilated into the theoretical model for equatorial plasma bubble formation to forecast the occurrence of scintillation and the magnitude of amplitude scintillation index (S_4).

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